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CONTAMINATION FROM SKYLAB AS DETERMINED FROM THE SOLAR CORONAGRAPH DATA

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December 1976

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Marshall Space Flight Center, Alabama

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16. ABSTRACT

The white light solar coronagraph was one of the scientific telescopes flown on Skylab to study the Sun. It studied the Sun's atmosphere located from 0.5 to 5.0 solar radii above the Sun's limb. Such a telescope is so sensitive to contamination around the spacecraft that it caused a major contamination abatement program to be initiated at the conception of Skylab. This report analyzes the coronagraph's data, showing the successfulness of that abatement program.

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TECHNICAL MEMORANDUM X-73353

CONTAMINATION FROM SKYLAB AS DETERMINED FROM THE SOLAR CORONAGRAPH DATA

INTRODUCTION

In 1965 Dr. John A. Eddy wrote a High Altitude Observatory Memorandum describing the qualitative aspects of deposited debris on a white light solar coronagraph proposed for a post-Apollo manned scientific program. That program evolved into Skylab [1,2], the first United States space station. In a 1967 article Dr. Gordon Newkirk, Jr., described the quantitative limits of floating debris on the coronagraph's operation [3]. This article predicted that the contamination around Skylab would barely allow the coronagraph to observe the solar corona and suggested that all wastes be placed in disposable sealed packages. The article brought about a flurry of articles concerning contamination and resulted in a concerted effort by NASA to control the contamination around Skylab. One resulting article by Dr. Natalie Kovar [4] showed that the observation of the solar corona from Skylab would not be possible. Mr. George Bonner proposed flying a less-sensitive coronagraph on one of the manned lunar flights to learn more about the contamination problem.

The Bonner coronagraph never flew on a lunar mission but did eventually fly on Skylab. All available evidence of lunar flight contamination was extensively examined. In the construction of Skylab, NASA changed nozzle design to reduce particle production, bagged the majority of the wastes and placed them into a waste tank, made overboard dumps as a contingency only (under normal practice the dumps would go into the waste tank), enforced clean room standards in the fabrication of the vehicle, performed extensive testing, and created a contamination evaluation group which operated during the Skylab mission to control contamination. Because of back pressure from bacterial action in the waste material that would result in leakage into the crew compartment, the waste tank was vented to space. To avoid the possibility of dumping liquid water or saturated vapor through the external vents of the waste tank, the partial pressure in the waste tank was to be kept below the triple point of water.

Ice which formed from the water that was dumped into the waste tank was kept from the vents by placing an ultrafine mesh screen around the dump line exits and around the vents. Figure 1 shows the waste tank geometry, and Figure 2 shows an electron micrograph of the ultrafine screen. The maximum size particle capable of passing through the screen was 9 μ. The nominal size to pass through was 2 μ.

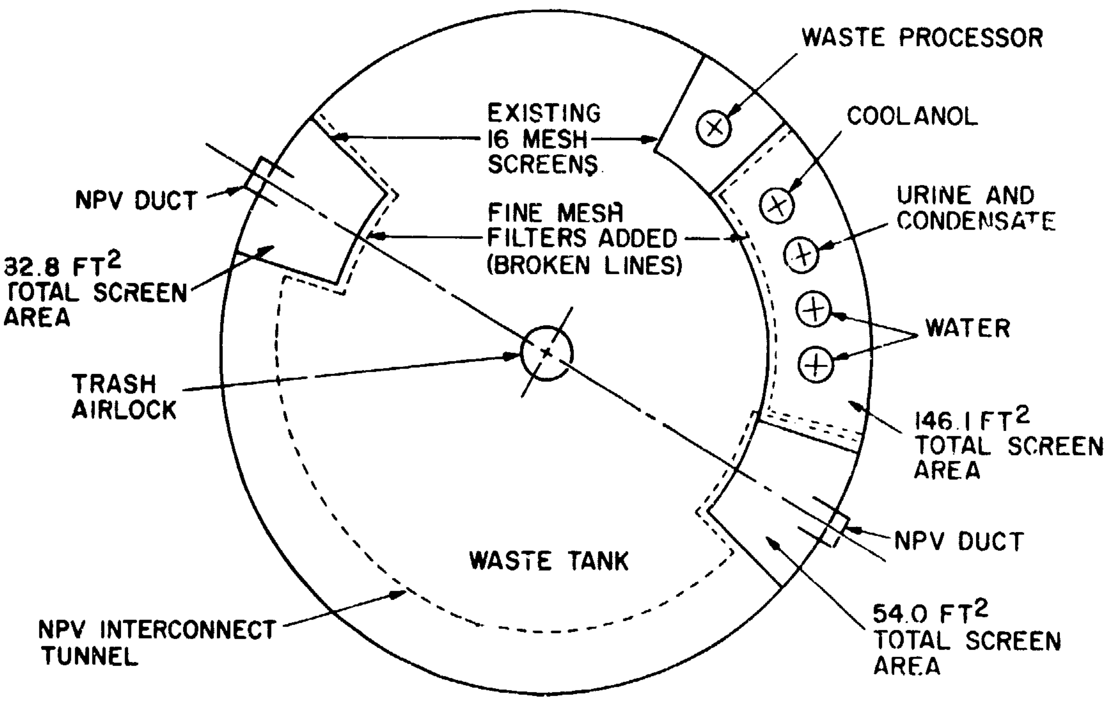
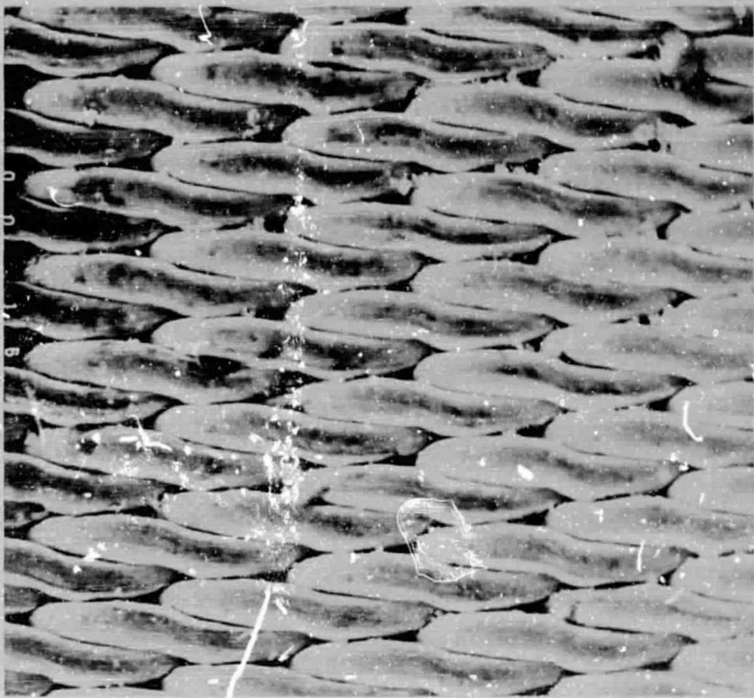
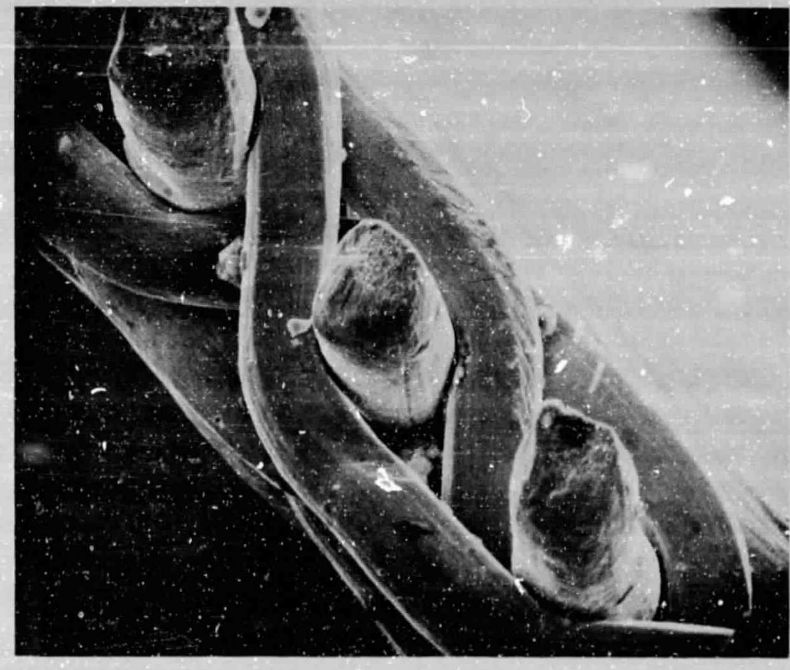


Figure 1. Skylab waste tank configuration.

The coronagraph which aroused the interest in contamination around Skylab will be described and the analysis of its contamination data examined. The study will include an analysis of Skylab's induced atmosphere (an atmosphere produced by micron and submicron particles where the combined scattering of the particles produces a bright uniform background) and the distinguishable particles emitted from the spacecraft.



(a) Trapped urine particles, 300 X.



(b) Side view, 500 X.

Figure 2. Scanning electron micrograph of the stainless steel "Dutch Twill" screens used as filters in the Skylab waste tank.

DESCRIPTION OF THE TELESCOPE

The coronagraph was of a Lyot design; that is, it had a primary lens plus an occulting disk behind that lens to block out the Sun's disk. In addition to that basic Lyot design, it incorporated an aligned series of three external apodized occulting disks at a distance of 229 cm in front of the primary lens. The optical layout is shown in Figure 3, and the instrument layout in Figure 4. Table 1 gives the basic parameters of the system. The instrument had an angular field of view extending from 0.4° to 1.6° from the center of the Sun. The stray light was less than 2.3×10^{-10} $B_{\odot}$ in the outer field of view, where $B_{\odot}$ is the mean radiance of the solar disk [5]. All the scientific data were taken with a film camera. A television system was provided to allow the astronauts to have a real time observation of the corona and to help the ground-based investigators determine the near real time mission planning. A more complete description of the instrument has been given by MacQueen et al. [6,7] and by Ross [8].

INDUCED ATMOSPHERE

Skylab's induced atmosphere is defined as that produced by so many particles that their combined scattering produces a bright uniform background. It was this induced atmosphere that was a primary concern to the experiment investigators. The particles of concern in this category are the micron, submicron, and molecular sizes. Since Skylab's orbital altitude was approximately 430 km, the aerodynamic drag is the predominant clearing force. The molecules are swept away almost immediately and, therefore, are of no concern. In terms of equal number of particles, the submicron particles are poorer forward scatterers than the micron particles. Therefore, the worst case is assumed and the micron size particles are used in determining the amount of induced atmosphere. The radiance from a micron size induced atmosphere can be calculated from [3]

$$\frac{B}{B_{\odot}} = \Omega_{\odot} M \bar{\sigma}$$

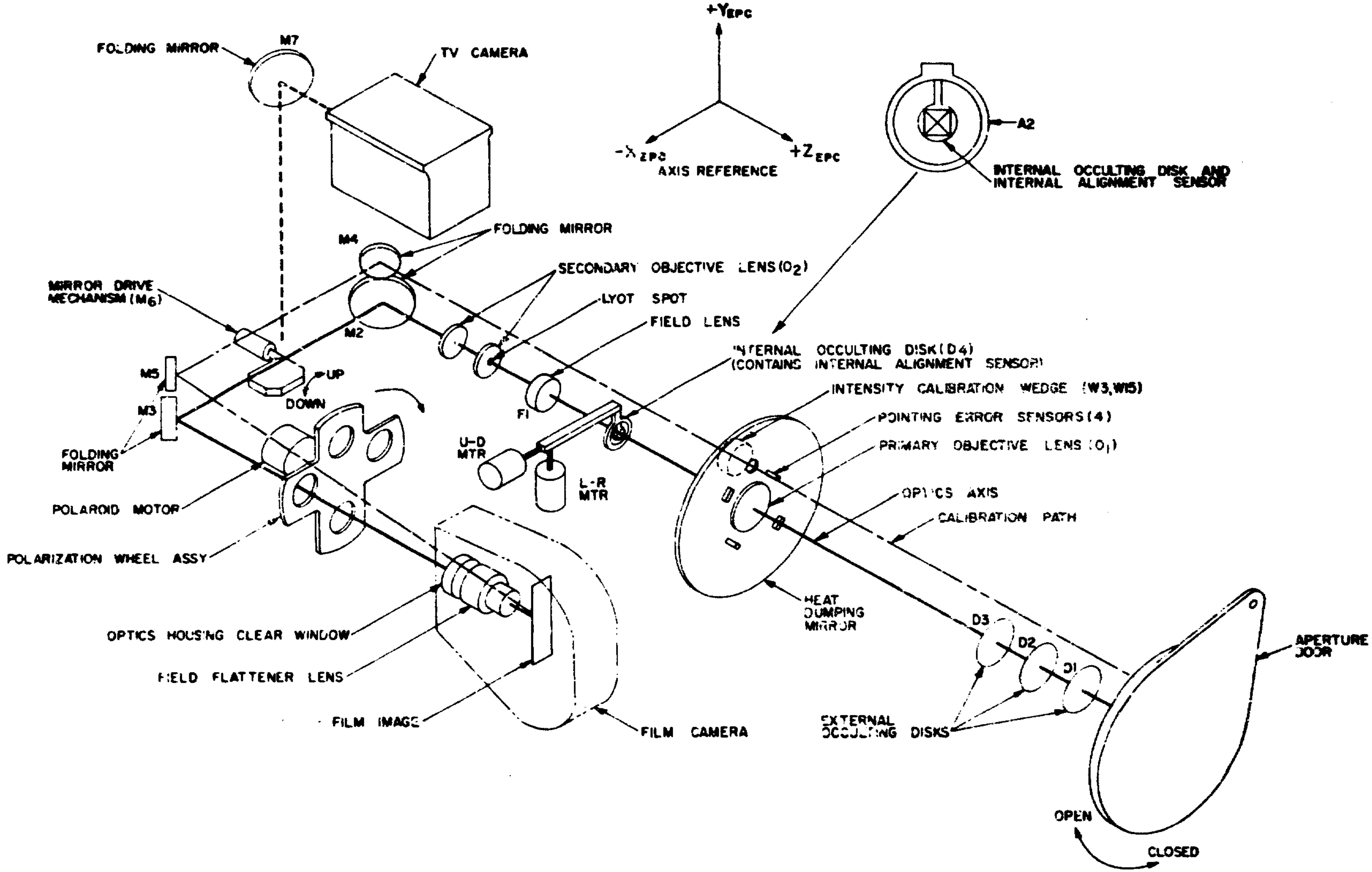


Figure 3. Schematic of the optical unit for the solar white light coronagraph.

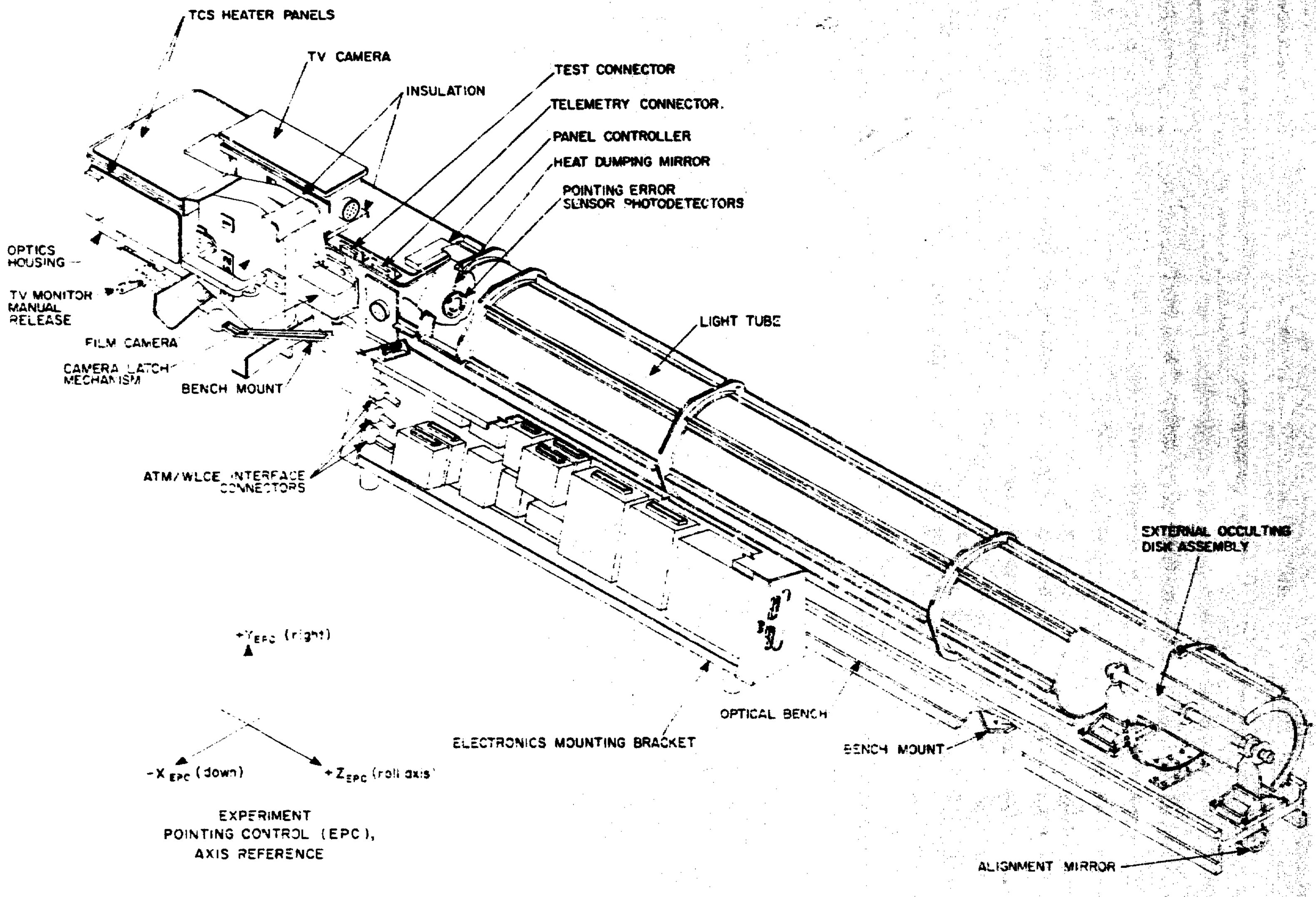


Figure 4. Solar white light coronagraph.

TABLE 1. TELESCOPE SPECIFICATIONS

Aperture diameter: 32 mm

Calibration wedge: 19-step from 3×10^{-6} to 1×10^{-10} $B_{\odot}$ ($B_{\odot}$ is the radiance of the mean solar disk)

Exposure times: 3, 9, and 27 s

Field of view: 24 to 96 arc min for film camera, 24 to 72 arc min for TV system

Field of view obstruction: 19 percent for film system

Film scale: 486 arc s/mm

Film size: perforated 35 mm, 1000 ft rolls

Film type: Kodak Special Film 026-02

Filters: clear, Polaroid displaced 0°, Polaroid displaced 120°, Polaroid displaced 240°

f number: 13.7

Focal length: 437 mm

Resolution: 8 arc s

Spectral range: 3700 to 7000 Å

Vignetting: 0.01 transmission at 24 arc min, increasing to 1.0 transmission at 80 arc min.

where

B = radiance from the scattering atmosphere

$B_{\odot}$ = mean radiance of the solar disk

$\Omega_{\odot}$ = solid angle subtended by the Sun

M = column density

$\bar{\sigma}$ = total Mie scattering function.

Sublimation time for the ice particles is long enough that it need not be considered in the calculations [3, 9].

The white light solar coronagraph imaged a step wedge on each picture frame by a supplementary optical system. This wedge was illuminated by sunlight and calibrated relative to the intensity of the mean solar disk. Using this calibration technique, it was determined that the induced atmosphere around the spacecraft was no greater than 2.3×10^{-10} $B/B_{\odot}$ at 5.0 solar radii.

The Martin-Marietta Corporation contamination group[1] determined that for each day during the normal manned operation of Skylab, 5480 grams of water were lost. Water is considered by far the major contributor to the induced atmosphere. The loss was due to minor leaks in the living area, normal reconditioning of the atmosphere in the living area, and the use of the waste disposal system. Placing this information into the previously mentioned model, one learns that less than 0.9 percent of this water turned into ice with a mean radius of $3\,\mu$ and velocity of 3×10^4 cm/s (Fig. 5). It was assumed that the background was due to scattering from these particles. In reality, internal scattering of the telescope was the major contributor to the background.

Examination of the white light solar coronagraph's photographs of stellar images reveals another aspect of the background illumination. The apparent brightness of a stellar point is increased by passing its radiation through a lens system. The brightness of a point image varies solely with D, the aperture diameter. Thus, the magnitude of the faintest star shown on a given film with a given exposure depends upon the diameter of the lens. The photographic

[1]Private communication

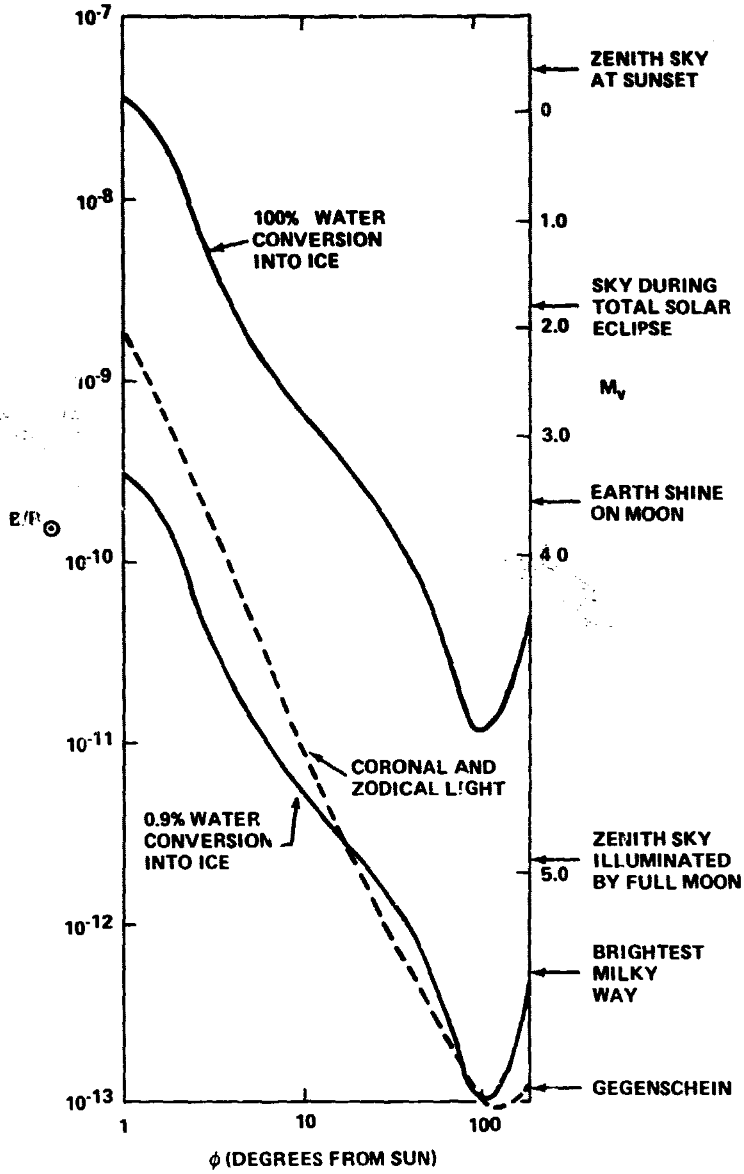


Figure 5. Theoretical results using Mie scattering theory. (This shows what the background illumination would be if the water were dumped at a constant rate and it was assumed that all turned into ice with a mean radius of 3 μ. Also shown is the illumination background curve for the case in which 0.9 percent of the water, dumped at a constant rate, is turned into ice with a mean radius of 3 μ. This was the worst possible case observed by the solar white light coronagraph. The limiting magnitude m_V for stars seen against a background with the unaided eye appears as an alternate scale of radiance together with that of several extended astronomical sources).

magnitude expected for the white light solar coronagraph is

$$m_p = 5 \log D\,(\text{in.}) + 2.15 \log E\,(\text{min} + 7.2) \quad ,$$

$$\text{for } 9\text{ s } m_p = 5.9 \quad , \quad \text{and}$$

$$\text{for } 27\text{ s } m_p = 7 \quad .$$

If the empirical formulas developed by Dr. Tousey and Dr. Koomen [10] are used, one obtains the fact that 7.0 magnitude stars should be seen with the 2.3×10^{-10} $B_{\odot}$ background. Table 2 gives a list of some of the stars seen by S-052. The faintest seen was 7.0 magnitude, which agrees with the previously discussed expectations.

TABLE 2. SOME OF THE STARS OBSERVED BY S-052

Camera	Magnitude Number	Yale Number	Smithsonian Number
1	5.7	1471	
1	6.0	1459	
1	4.3	1497	
1	5.4	1659	
1	4.6	1620	
1	5.8	1586	
2	6.3	2240	
2	3.2	2216	
2	5.8	2173	
2	5.9	2185	
2	3.0	2286	
2	6.0	2304	
2	6.0	2810	
2	3.5	2777	
2	1.4	3982	

TABLE 2. (Continued)

Camera	Magnitude Number	Yale Number	Smithsonian Number
2	5.2	3937	
3	6.0	4101	
3	5.6	4088	
3	3.8	4133	
3	5.6	4148	
3	5.9	4267	
3	4.6	4310	
3	5.6	4294	
3	3.6	4540	
3	6.4	4580	
3	6.1	4533	
4	6.2	5756	
4	5.5	5762	
4	4.7	5838	
4	5.0	5902	
4	2.6	5984	
.	4.0	5993	
4	4.3	5997	
4	4.6	6112	
4	5.4	6424	
4	4.2	6486	
4	4.8	6519	
4	6.6	6515	
4	4.8	6700	
4	5.7	6716	
4	5.4	7624	
4	6.0	6736	
4	5.1	6801	
5	5.7	6961	
5	5.8	6990	
5	6.4	6965	
5	6.1	7011	
5	5.8	7046	
5	6.2	7088	

TABLE 2. (Concluded)

Camera	Magnitude Number	Yale Number	Smithsonian Number
5	6.7		187381
5	4.8	7116	
5	5.0	7120	
5	5.9	7128	
5	6.0	7159	
5	5.8	7114	
5	3.8	7217	
5	6.3	7182	
5	2.9	7264	
5	5.6	7327	
5	5.6	7375	
5	6.0	7410	
5	6.7		188317
5	5.0	7515	
5	6.7		188580
5	6.9		163107
5	7.0		163285
5	5.5	7761	
5	6.6		189142
5	5.2	7814	
5	6.7	7823	
5	4.8	7822	
5	5.1	7900	
5	6.4	7964	
5	5.9	8000	
5	6.7		163973
5	6.5		164061
5	5.9	8018	
5	4.0	8075	
5	6.0	8083	

PARTICULATE CONTAMINATION

Particulate contamination is defined as the case in which individual particles can be seen by the tracks they make. The brightness per unit area on the film for a given size particle will remain constant from the objective lens to the hyperfocal distance, that is, the point at which the lens perceives infinity to begin. The hyperfocal distance for the solar white light coronagraph can be found from the expression [11]:

$$H = \frac{AF}{D}$$

where

H = hyperfocal distance

A = operative diameter

F = distance of the lens from the film plane

D = diameter of the resolution element of the system.

For this telescope the hyperfocal distance was 850 m. After the hyperfocal distance is reached, scattered light intensity of the particle falls off as $1/r^2$. Contamination was observed from the front of the telescope to infinity, with most of it being relatively close to the telescope. One particle was seen to float to the outer occulting disk. The outer occulting disk was periodically cleaned by the astronauts during their extravehicular activities. Figure 6 shows a most objectionable case of particulate contamination. Figure 7 shows the more common contamination problem from Skylab, which is less objectionable than the previous case.

The film data were the prime source for the analysis of particulate contamination. The TV data had poor resolution, did not include the whole field of view, were preselected by the astronauts, and had a poor signal-to-noise ratio. Figure 8 is an example of the TV image.

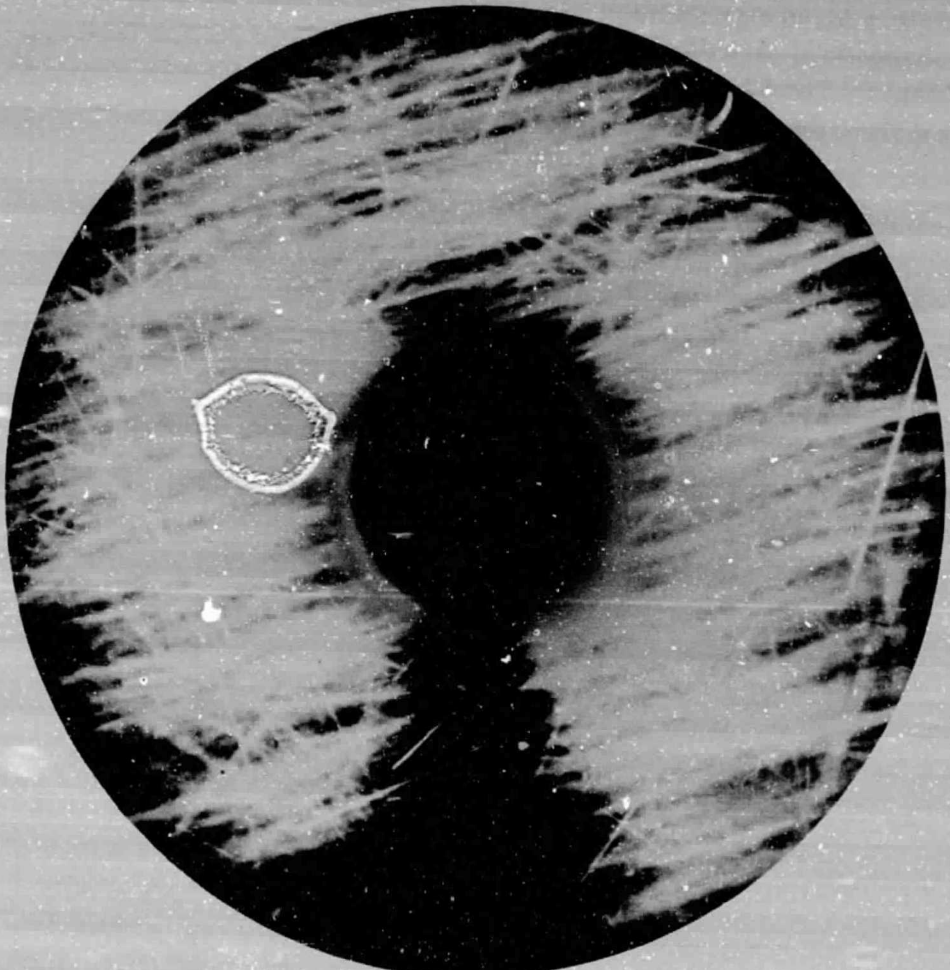


Figure 6. An overabundance of particulate contamination in the field of view of the telescope.

Figure 7. A particle of contamination in the field of view of the telescope.

The telescope sequenced through three exposure times (3, 9, and 27 s) with any one of four filters (three polarized filters plus a clear position). For the clear filter position, the 3 s exposure was underexposed for the purpose of studying the inner corona. The 9 s exposure was the best exposure for studying the majority of the corona. The 27 s exposure was overexposed for the purpose of studying the outer corona.

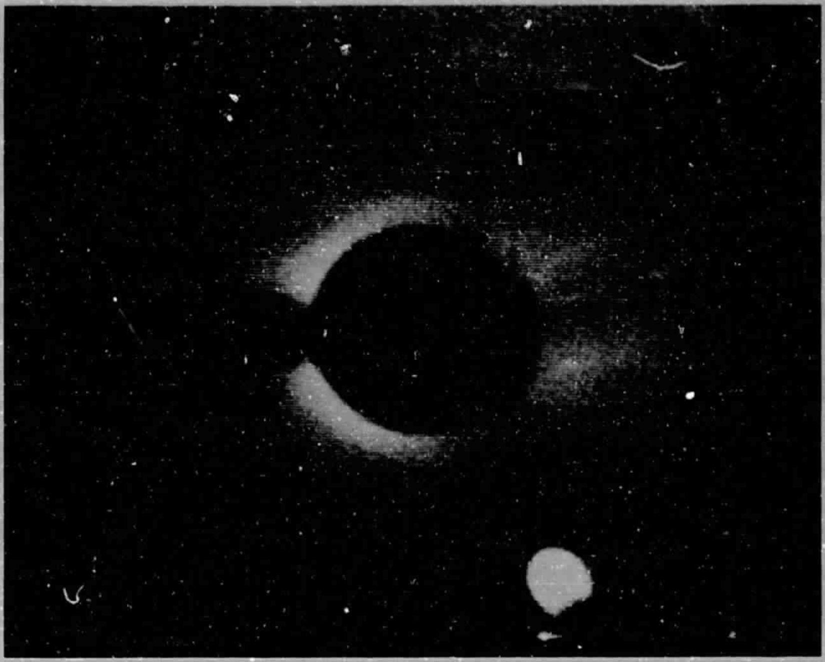


Figure 8. A photograph of the telescope TV monitor showing a particle of contamination.

The 9 and 27 s clear exposures were the pictures examined for particulate contamination. First generation copies were used. For the first 1000 frames taken, the camera advance tended to slip, causing an overlapping of some frames and a confusion of the data in the corona pictures. Therefore, those pictures were eliminated from the analysis. The 12 039 pictures that were thoroughly examined were all the remaining 9 and 27 s clear exposures. The first generation copies were optimized for visual use; therefore, the 27 s exposure copies were underexposed. In the analysis of the results of the particulate contamination, it was found that because of the underexposing of the overexposed 27 s exposures, those frames yielded less information than the 9 s exposures. Therefore, 6065 frames of 9 s exposures were the primary source of data on particulate contamination, and the 5974 frames of 27 s exposures were used only for supportive data.

In the analysis of the data, it was decided to divide the particulate contamination into two categories, one being "event contamination" and the other "random contamination." The event contamination is defined as that in which

(a) three or more particles are seen on two (9 and 27 s exposures) or more consecutive frames, or (b) six or more particles are seen on two (9 and 27 s exposures) or more consecutive frames. The random particulate contamination was all other particulate contamination.

The event type of particulate contamination is shown in Table 3, which also shows when the event was first observed by the telescope. None of these events could be correlated with any of the Skylab activities because of insufficient housekeeping data. One of the TV downlinks showed an event contamination which was correlated to a water dump. The photographs of one occurrence of event type contamination were analyzed [12] using the diffraction scattering theory plus the hyperfocal distance formula but using H to represent the distance between the object and the telescope and D to represent the diameter of the out-of-focus image. These results showed the ice particles to range in size between 6 and 130 μ and their transverse velocities to range between 0.03 and 0.72 m/s with the average being 0.122 m/s. The radial velocities varied between 0.4 and 31.0 m/s. The particles were from 16 to 247 m away from the objective lens. The average distance of the particles was 73 m in front of the optics, or approximately 71 m in front of the telescope.

For one of these events, the trajectories were analyzed to determine whether the aerodynamic drag was causing some of them to be curved. Using

$$m_o a = n\, m_A \nu v \quad ,$$

where

m_o = mass of the particle

n = number of particles

m_A = mass of the atmosphere

v = the relative velocity,

TABLE 3. EVENT PARTICULATE CONTAMINATION

	Dumps		
	DOY	Time (GMT)	Class
1	159	02:14	A
2	170	22:20	B
3	183	13:41	B
4	185	18:53	B
5	210	01:46	B
6	211	05:32	B
7	214	14:00	A
8	219	04:46	B
9	235	13:44	B
10	236	00:53	B
11	237	01:19	B
12	239	12:27	B
13	247	09:51	B
14	249	09:58	B
15	250	21:00	B
16	261	20:59	B
17	333	00:17	B
18	338	02:46	B
19	339	02:14	B
20	339	10:40	B
21	341	12:18	B
22	360	05:29	B
23	361	18:50	B
24	12	12:22	B
25	14	01:16	B
26	14	13:44	B
27	16	00:40	B
28	17	06:48	B
29	17	22:24	B
30	19	23:39	B
31	32	13:31	B

A = more than 100 particles   B = less than 100 particles

	$4\text{-}10^h$ GMT	$10\text{-}16^h$ GMT	$16\text{-}22^h$ GMT	$22\text{-}4^h$ GMT
Mission 1				A, B,
Mission 2	B, B, B, B,	A, B, B,	B, B,	B, B, B
Mission 3	B, B,	B, B, B, B,	B	B, B, B, B

and [13]

$$\nu = 4\sqrt{\frac{2}{\pi}}\, n_A \sigma v \quad ,$$

where n_A = number density of the atmosphere and σ = collisional cross section, one can then obtain the change in velocity of the contamination particle due to drag. The result is

$$\Delta v = \frac{4\, v^2 \rho_{atom} T}{\rho_p D}$$

where

ρ_{atom} = density of the atmosphere

ρ_p = density of the particle

D = diameter of the particle

T = time.

The vectors of the spacecraft and the atmosphere for the altitude of Skylab [14] were used in the analysis. The particles were assumed to be ice. The results showed that drag could easily explain the curvature seen in the photographs.

Table 4 presents the results of the random particulate contamination, which is shown as a function of mission and as a function of astronaut activity. The astronauts were asleep during the 4 to 10 hours GMT. Their morning hours were between 10 and 16 hours GMT, their afternoon hours were between 16 and 22 hours GMT, and their nighttime hours were between 22 and 24 hours GMT. The results show that with the exception of the time after December 30, 1973, there was significantly less particulate contamination when the astronauts were asleep as opposed to when they were awake. During their waking hours, they bounced around Skylab, possibly causing outside debris to flake off. They perspired

TABLE 4. RANDOM PARTICULATE CONTAMINATION (9 s EXPOSURES)

Missions	Portion of Day GMT (h)	Number of Frames	Number of Particles	Frames/ Particle	Particles/ steradian/s
1	4-10	347	24	14.46	3.9
	10-16	146	9	16.22	3.5
	16-22	137	11	12.45	4.5
	22-4	176	25	7.04	8.0
2	4-10	745	45	16.55	3.4
	10-16	750	66	11.36	4.9
	16-22	403	58	6.95	8.1
	22-4	819	69	11.87	4.7
3	4-10	268	22	12.15	4.6
	10-16	908	49	18.53	3.0
	16-22	627	61	10.28	5.4
	22-4	737	74	9.96	5.6
1 + 2 + 3	4-10	1 360	91	14.44	3.7
	10-16	1 804	124	14.55	3.8
	16-22	1 167	130	8.98	6.2
	22-4	11 737	168	10.31	5.4
Between Missions		227	16	14.19	3.9
Mission 3 to Jan 1	4-10	221	10	22.10	2.5
	10-16	477	25	19.08	2.9
	16-22	397	31	12.81	4.4
	22-4	457	58	7.88	7.1
Mission 3 after Dec 30	4-10	47	12	3.92	14.3
	10-16	431	24	17.96	3.1
	16-22	230	30	7.67	7.3
	22-4	280	16	17.50	3.2
Mission 1 + 2 + 3 minus Mission after Dec 30	4-10	1 313	79	16.62	3.4
	10-16	1 373	100	13.73	4.1
	16-22	937	100	9.37	6.0
	22-4	1 452	152	9.55	5.9

more, causing the air reconditioning unit to vent more water to the outside. Garbage was disposed of through the trash airlock to the waste tank which was vented to the outside.

After December 30, the greatest amount of particulate contamination occurred when the astronauts were asleep. It was during this period of the mission that the astronauts began dumping their urine into the waste tank from the urine bags because of a shortage of urine bags as a result of the extension of the mission. It was also during this portion of the mission that the urine bags that were dumped into the waste tank began breaking. The activity of dumping the urine and urine bags into the waste tank during this portion of the mission occurred just prior to sleep time. It is most likely that this dumping caused the excess of contamination during the astronauts' sleep hours.

The particulate contamination between missions was 3.9 particles/steradian/s, which was greater than the 2.5 particles/steradian/s observed during the astronauts' sleep time for the first portion of the third mission. The possible explanation for this is that the external cooling system leaked significantly more when Skylab was unmanned than when it was manned.

There were 23 particles which appeared to be 850 m from the telescope. From these it was found that the velocities, parallel to the telescope, ranged from 0.2 to 1.2 m/s, with a nominal velocity of 0.4 m/s.

The minimum size particle that could be seen with the telescope can be determined by using diffraction scattering theory [15]. The theory states

$$\frac{I}{I_o} = \frac{\pi a^2}{\lambda^2 r^2}\left[\frac{2\,J_1\,(x \sin\theta)}{x \sin\theta}\right]^2$$

where

a = particle radius

I_o = incident intensity

J_1 = first order Bessel function

r = distance from the particle to the telescope

$x = 2\pi a/\lambda$

θ = scattering angle

λ = wavelength.

For our case,

$$\lambda = 0.5 \quad ,$$

$$r = 850 \text{ m} \quad ,$$

$$I_o = 1.39 \times 10^6 \text{ erg s}^{-1} \text{ cm}^{-2} \quad ,$$

and

$$\theta = 1° \quad .$$

It is assumed that the particles are spheres of ice. The resolution element of the system was 3.88×10^{-5} radians. Therefore, each resolution element was exposed for 0.165 s by a particle traveling 0.2 m/s. Table 5 presents various size particles, the intensity from the particle, and the intensity which the resolution element would experience.

To estimate a lower limit for the radiance that can be detected, it is assumed that any deviation greater than 5 percent above the background radiance (K + F coronal radiance and stray light) would have been detected. Assuming that a value of 1×10^{-9} $B_\odot$ is representative of the background radiance present in our measurement, the 5 percent deviation limit corresponds to a minimum value of 5×10^{-11} $B_\odot$. This corresponds to 1.08×10^{-8} ergs cm^{-2} for a 9 s exposure, which was the optimum photograph. From Table 5 it is seen that this means a radius of approximately 6μ would be the smallest expected ice particle that could be detected with this telescope.

TABLE 5. CALCULATED INTENSITIES

Radius (μ)	I (erg s^{-1} cm^{-2})	I (ergs cm^{-2})
1	7.45×10^{-11}	1.23×10^{-11}
2	1.15×10^{-9}	1.90×10^{-10}
3	5.50×10^{-9}	9.06×10^{-10}
4	1.60×10^{-8}	2.64×10^{-9}
5	3.49×10^{-8}	5.76×10^{-9}
6	6.25×10^{-8}	1.03×10^{-8}
7	9.75×10^{-8}	1.61×10^{-8}
8.2	1.43×10^{-7}	2.36×10^{-8}

DISCUSSION

The solar white light coronagraph was a scientific observational telescope so sensitive to contamination around Skylab that it was one of the best detectors for the contamination. The biggest concern to the investigators was that the induced atmosphere around the spacecraft would be of such a magnitude that it would not allow observations of the solar corona. No induced atmosphere, as far as can be determined, was observed by this telescope. This substantiates the fact that the contamination photometer flown on the first mission did not observe one [16]. It had a sensitivity of 1.2×10^{-15} $B_{\odot}$ for the dark side of the orbit.

Individual particles were observed with the telescope. The number was so great on two occasions that it masked the coronal film data. At another time, a similar type of contamination was seen on TV during an unauthorized contingency condensate venting. Therefore, it is assumed that the previous two events were also caused by some gross venting. There were other times

when quite a few particles were seen but not so many as to hinder the coronal data. It is assumed that these occurrences were due to some event which dislodged a group of particles which had accumulated near an orifice but were not due to a gross venting.

Most of the time individual particles were seen. The origin of these particles was probably from some vent or leak. From the thorough analysis of paint [17] on Skylab, it was concluded that with one exception the paint could not have caused any of the contamination. The exception is that there was some paint blistering on the CSM near the RCS engines due to engine operation. From the time profile of the contamination seen, it is deduced that the leak in the cooling system as well as the waste tank were probably contributors.

During the extravehicular activities, the astronauts had to clean the edge of the outer occulting disk of the telescope. Dust and whisker-size particles tended to collect there: therefore, some slight internal contamination was present. For a couple of orbits after the extravehicular activities, the astronauts observed large quantities of contamination on the TV system. This contamination was probably a residue from the frontal ventilation system in the astronauts' suits.

The contamination control group did a very good job in designing the items on Skylab to inhibit contamination. The solar white light coronagraph principal investigator was very pleased at the low level of contamination.

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APPROVAL

CONTAMINATION FROM SKYLAB AS DETERMINED FROM THE SOLAR CORONAGRAPH DATA

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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